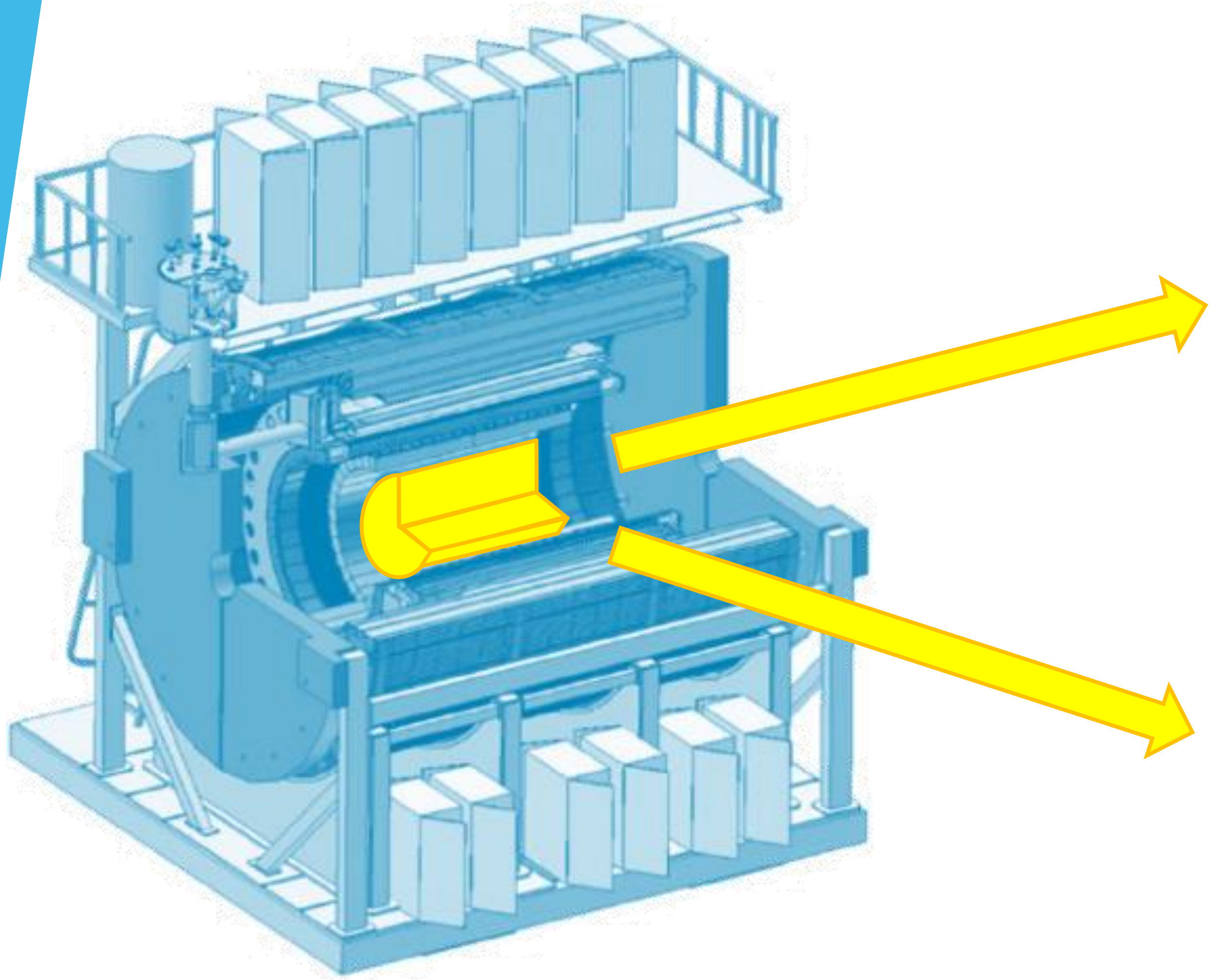
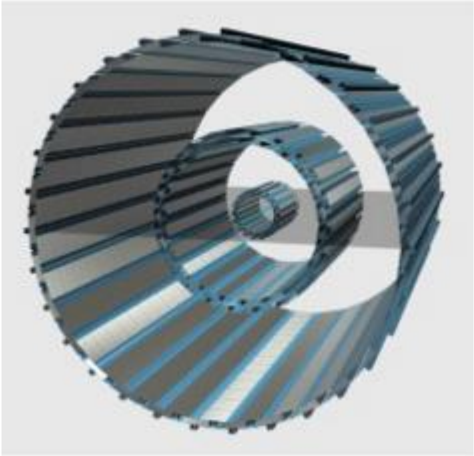
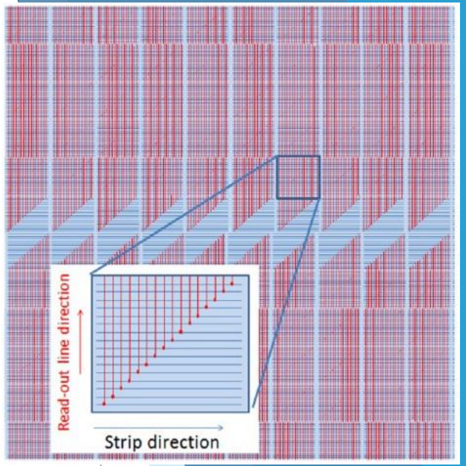
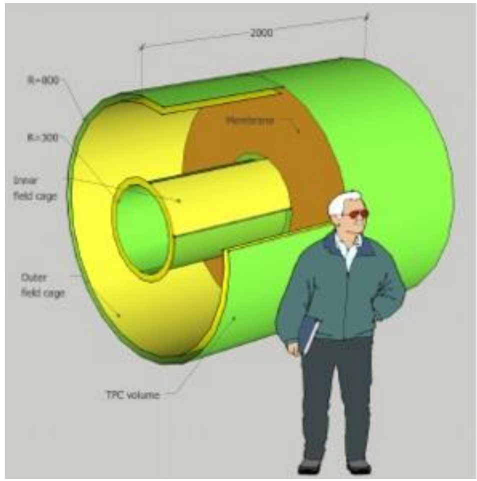
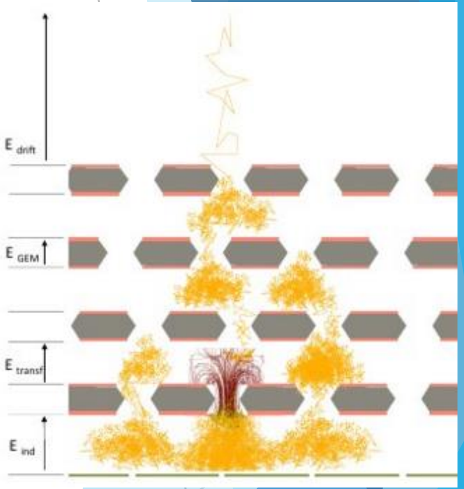










sPHENIX TPC Tracker

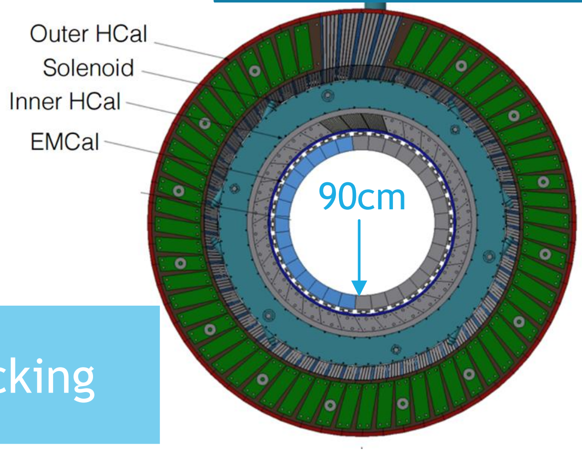
TK Hemmick

Detector Specifications

> "…we anticipate that the features and experience gained with this device might provide the basis for a "day-1" detector at a future EIC, independent of where the new facility will be sited. It is envisioned that this new collaboration will consider the possible evolution toward such a detector as part of its mission."
> --Berndt Mueller

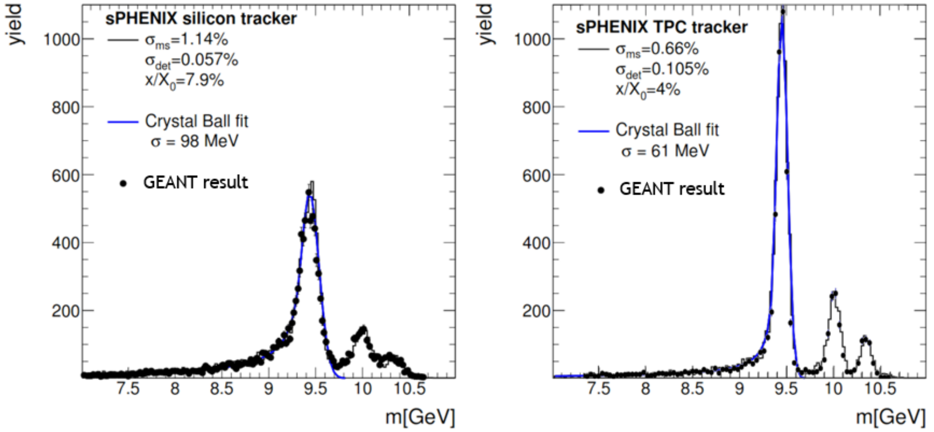
Entertaining options requires more work but generates the necessary flexibility.

- Mechanical Constraints (magnet/EMCal-driven)
  - EMCal Mechanical constraint @ r=90cm.
  - Physics defines aspect ratio: $|\eta| < 1.1$ or Length $\approx$ *Diameter*.
    - Current Tracker Confining Volume: Length = Diameter = 160cm.
- Physics program accomplished via two toughest constraints:
  - Mass resolution sufficient to resolve Upsilon States.
    - $\boldsymbol{\sigma_m < 100\ \frac{MeV}{c^2}\ @\ m \approx 9\ \frac{GeV}{c^2}}$ ← Outer Tracking
  - DCA Resolution sufficient for tagging heavy flavor secondary vertices.
    - $c\tau(D) = 123\ \mu m;\ \ c\tau(B) = 457\ \mu m$
    - $\boldsymbol{\sigma_{DCA} < 100\ \mu m}$ ← Inner Vertex
- Environmental constraints:
  - Central Au+Au multiplicity @ full RHIC Energy.
  - Full RHIC-II Luminosity



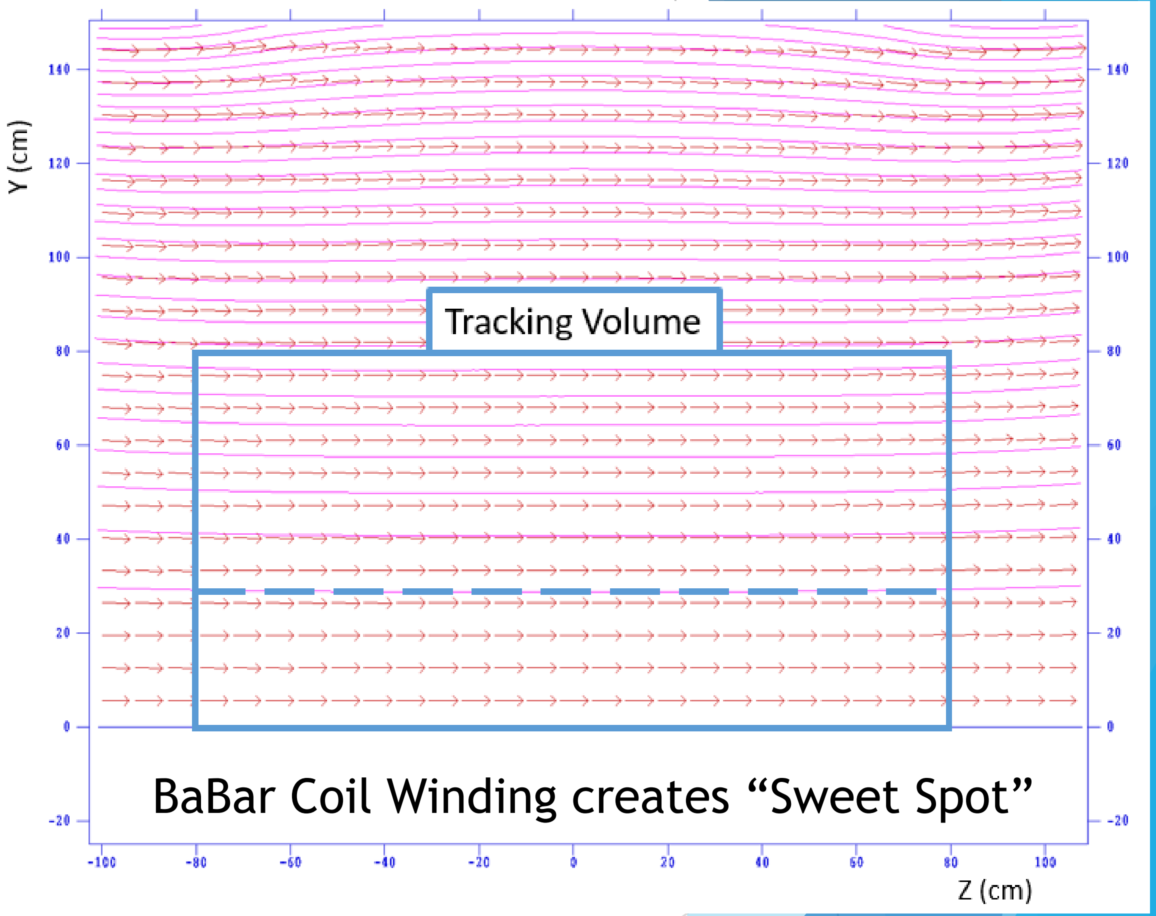
Mechanical Constraint

Physics Constraint



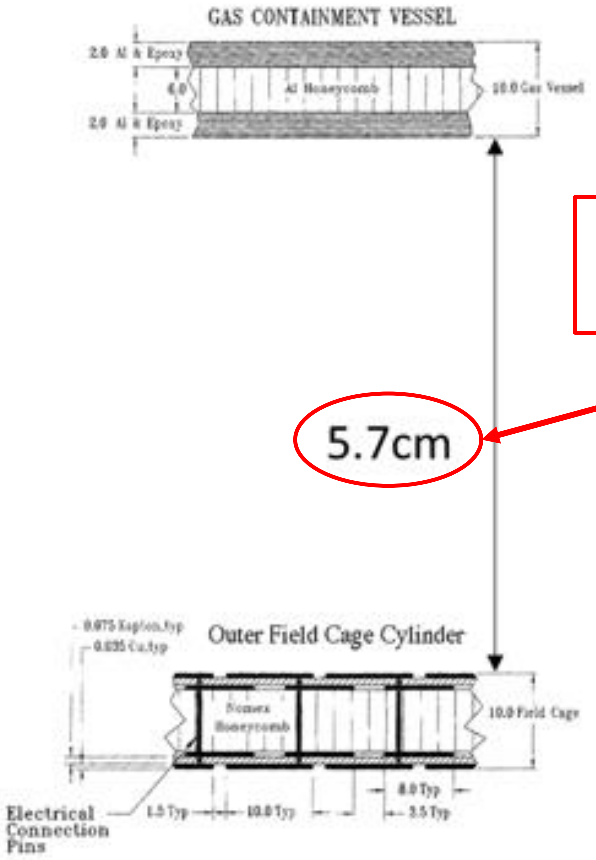
General Considerations

- The two largest TPC devices currently in use are STAR and ALICE.
- Our needs are well beyond the ability either of these devices as currently configured.
- However, our needs are surprisingly similar to the ALICE TPC following the planned upgrade:
  - Untriggered Rate: 50 kHz in both cases.
  - Single event particle density similar.
- All TPC devices require a reasonably uniform magnetic field. Thus can be achieved by:
  - STAR, pole tips with small opening.
  - BaBar nonuniform winding density at the ends to “pinch” the field, making sweet spot in the middle.
- BaBar magnet is ideally suited to a TPC tracker of our dimensions.



Field Cage Considerations

- STAR and ALICE both use “gas gap” (between field cage and outer shell).
- As will be shown later, the TPC performance will be limited principally by electric field distortions due to positive ion feedback.
- The desire for high ion drift speed affects two parameters in the TPC design:
  - Gas choice. Likely drives us to use Neon or possibly Helium as the noble component.
  - $v_d = KE$, pushes toward largest electric field.
- $\vec{E}_{STAR} = 135\frac{V}{cm}$; $\vec{E}_{ALICE,\,sPHENIX} = 400\frac{V}{cm}$
- 400 V/cm drift @ 80 cm = 32 kV. (STAR=27kV; ALICE=100kV).



Rule of Thumb: 1 kV/mm
Exceeded by factor of 2.1

- An “air gap” solution ala STAR or ALICE will not work for us. (equal safety factor to STAR requires $5.7cm\frac{32kV}{27kV} + 2cm \approx 9cm$!
- Must design a “solid” solution for HV holding.

Field Cage-2

- Solids hold way more voltage than gas.
- Risk of single point failure.
- Requires large safety factor!

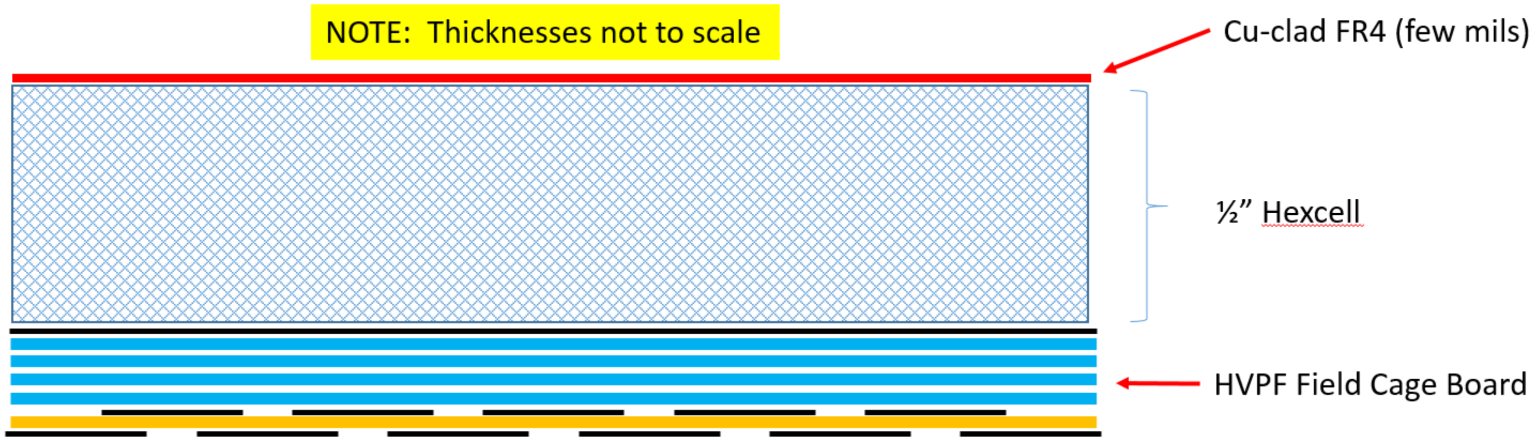
Material Type	Max. Operating Temperature (°C)	T/G °C	Voltage (V/mil) Note 1	Aged rating (V/mil)	W°C/m
FR4	**105-130**	**160**	**800**	**300/150**	**0.21**
FR4 Hi-Temp.	**130-150**	**170**	**800**	**300/150**	**0.22**
BT Epoxy	**140-160**	**180**	**1300**	**600/400**	**0.40**
Polyimide	**150-190**	**200**	**900**	**700/500**	**0.25**
HVPF*	**180-200**	**210**	**3000 to 7000**	**3000/2000**	**0.28**

***HVPF is a trademark of Sierra proto express.**

- Common HV materials age with time (e.g. standard FR4 "carbonized" air bubbles).
- Working w/ Palo Alto Co. to develop robust board.

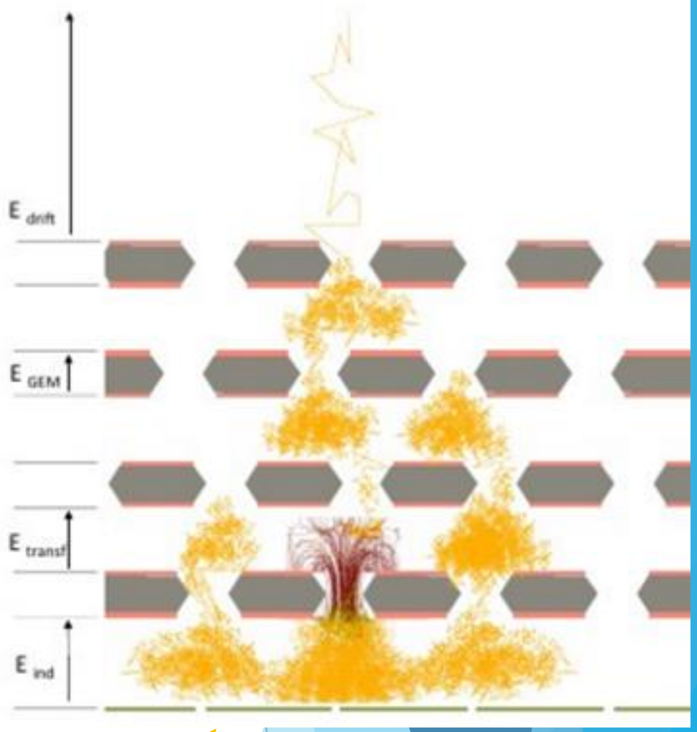
Material	χ_0 (cm)	Volt/mil	3X Safety	5X Safety
FR4	16.76	150	1.72 cm (10.3%χ_0)	2.88 cm(17.2%χ_0)
Kapton	28.58	500	0.52 cm (1.8%χ_0)	0.86 cm(3.0%χ_0)
HVPF	28.57	2000	0.13 cm (0.45%χ_0)	0.22 cm(0.75%χ_0)

NOTE: Shielded 100 kV cable has diameter 0.4 inches.

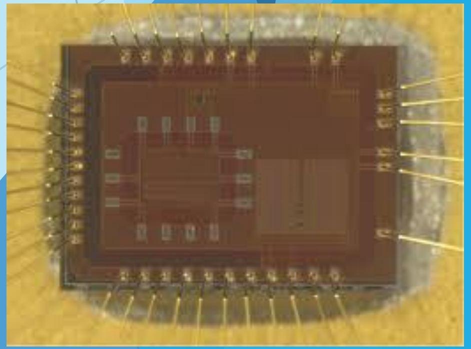


Next Generation TPC Concept

- Traditionally TPCs are considered as slow devices:
  - Long time to drift the primary ions to the gain stage.
  - LONGER time to dump these positive ions down the drain.
  - Operation cycle:
    - "Gate" is closed preventing positive ion back flow and electron drift to avalanche stage.
    - Trigger causes gate to open for period necessary to collect electrons.
    - Gate closes for period necessary to reject ions.
    - Device ready for next event.
- New concept coming out of STAR and ALICE experience.
  - "Stacked" events are not so big problem:
    - Independent event vertex.
    - Confirmation by "fast detector" or at least "different" detector.
  - Ion field distortion is manageable correction (STAR)
  - New device:
    - Gate-less design using gain stage w/ intrinsically low Ion Back Flow (IBF).
    - Continuous readout electronics (define event boundaries offline).



Micro Pattern Gas Detector



SAMPA Chip

MPGD Gain Stage

- Electron/Ion drift differences "enhanced" by staggered drift field options.
- Leads to four layers of GEM.
- Other considerations:
  - Hole pattern rotation.
  - Hole spacing changes.

NOTE: Unavoidable feedback 1st GEM

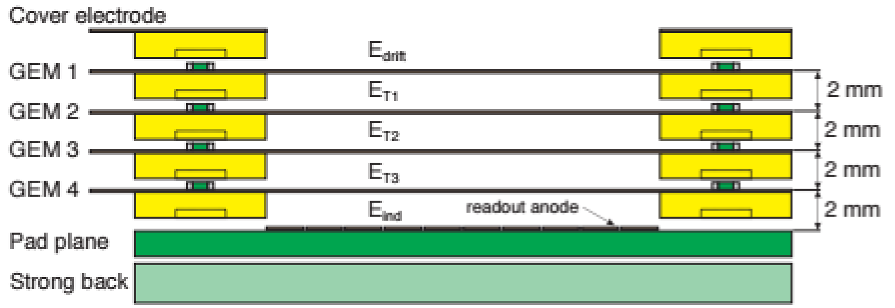


Figure 4.6: Schematic exploded cross section of the GEM stack. Each GEM foil is glued onto a 2 mm thick support frame defining the gap. The designations of the GEM foils and electric fields used in this TDR are also given. E_{drift} corresponds to the drift field, $E_{\mathrm{T}i}$ denote the transfer fields between GEM foils, and E_{ind} the induction field between the fourth GEM and the pad plane. The readout anode (see Eq. (4.2)) is indicated as well. The drift cathode is defined by the drift electrode not shown on this schematic.

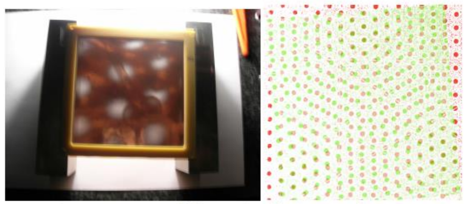


Figure 3.5: Left: Optical transparency of two standard GEM foils. Right: Illustration of the interference pattern that occurs when the foils are slightly rotated.

Moire

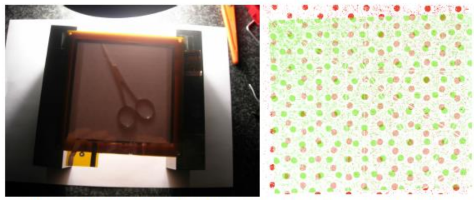


Figure 3.6: Left: Optical transparency of two standard GEM foils after rotation of one foil by 90°. Right: Illustration of the randomization of the relative hole positions.

Uniform

ALICE-USA builds this; roughly the same as our scale!

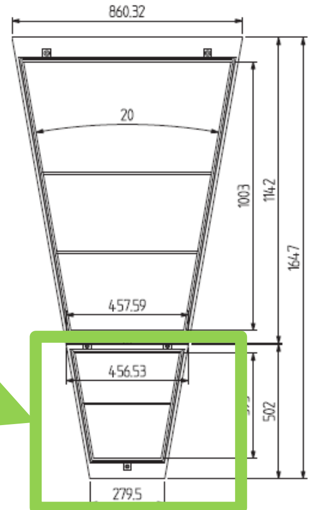


Figure 4.3: Dimensions (mm) of the ALICE TPC readout chambers.

40 cm

Figure 4.4 shows an exploded view of a GEM IROC. It consists of the following components:

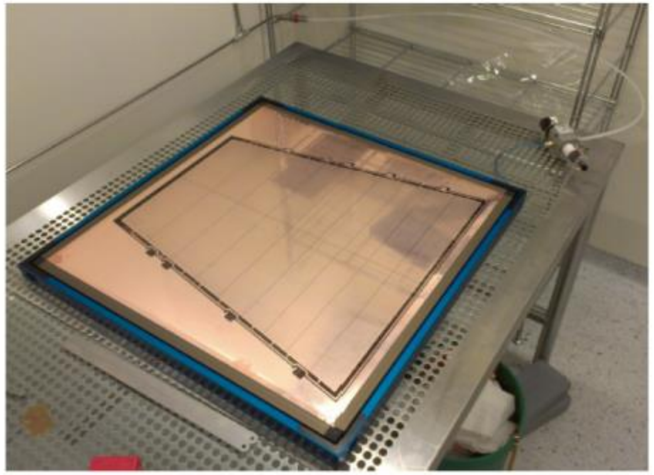


Figure 4.7: Photograph of an IROC GEM foil in the stretching frame.

Ion Back Flow

- Ion Back Flow measurements are receiving attention as never before.
- Both Yale (EIC/ALICE) and Munich (ALICE) have performed extensive measurements.
- Universal (natural) trend emerges:
  - Since IBF from 1st GEM is ~100%, the IBF is controlled by GEM1 gain.
  - Fluctuations in 1st stage gain define limiting energy resolution.
- Gain stage has TUNABLE performance
  - Ion+Ion … low IBF
  - e+Ion … good E-resolution for PID.

ALICE does not have this luxury, we do!

Quad-GEM Solution for ALICE

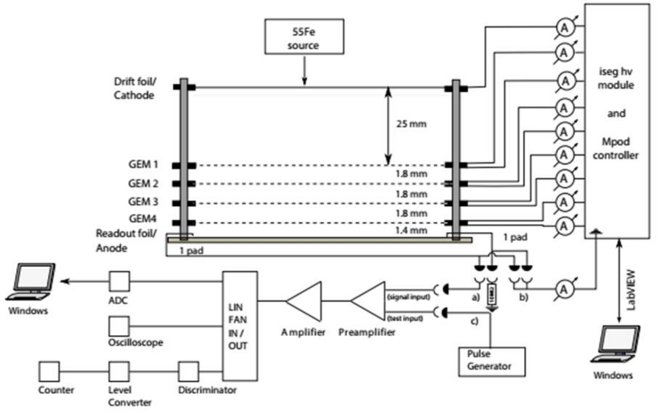
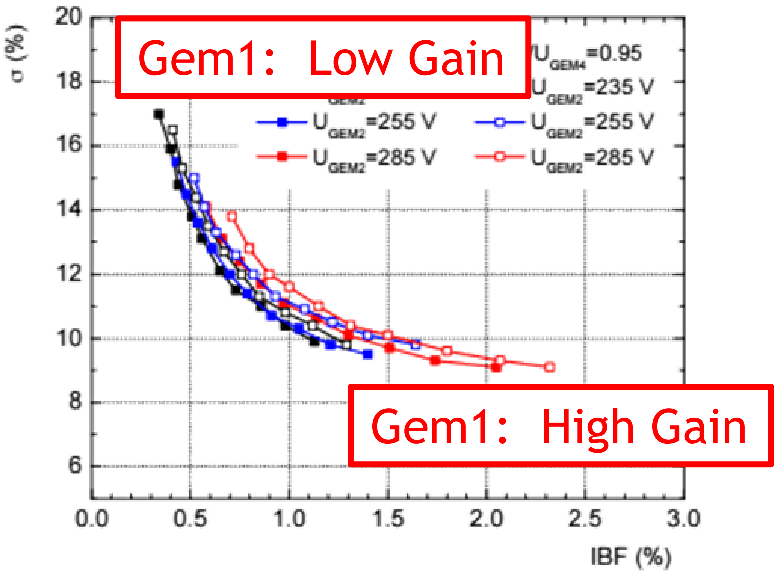
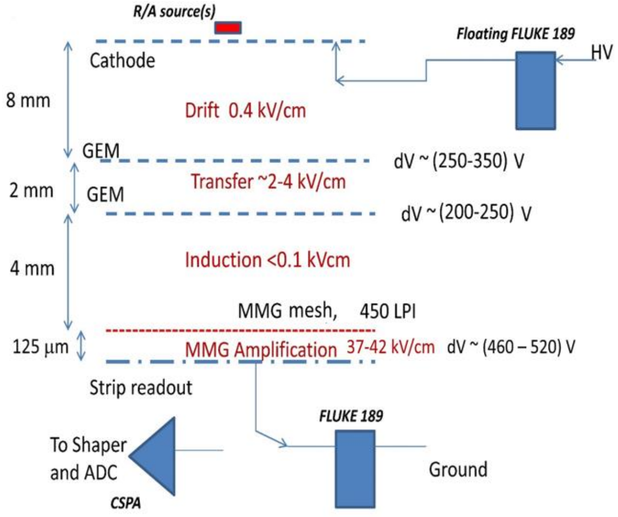
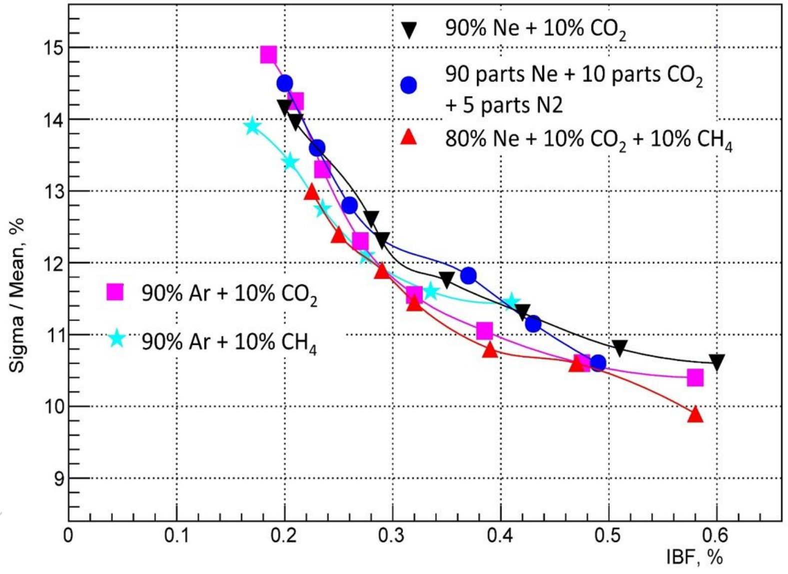


Figure 5.1: Sketch of the Munich quadruple GEM setup.

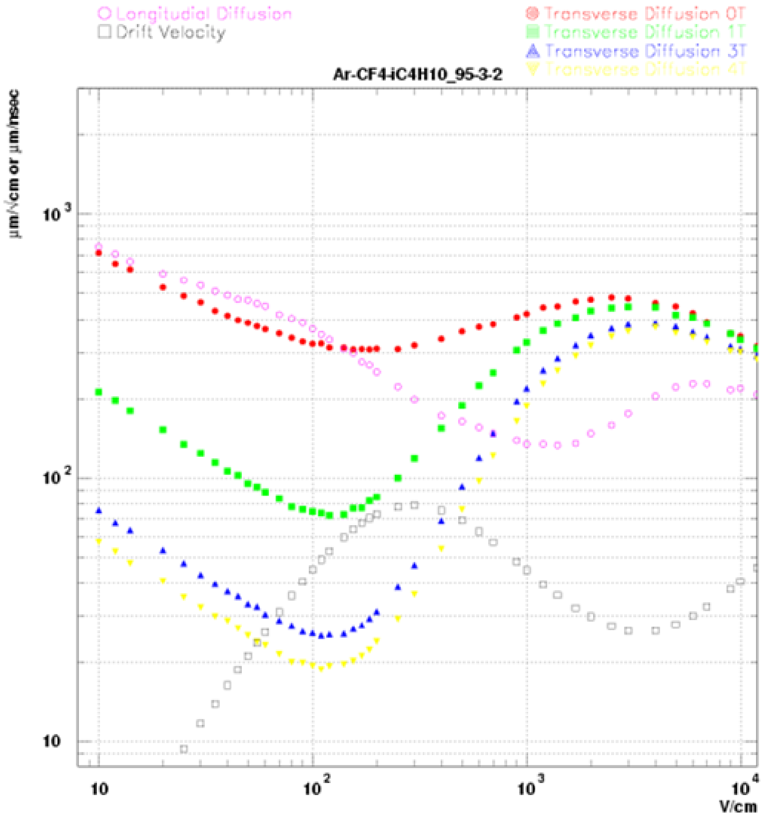


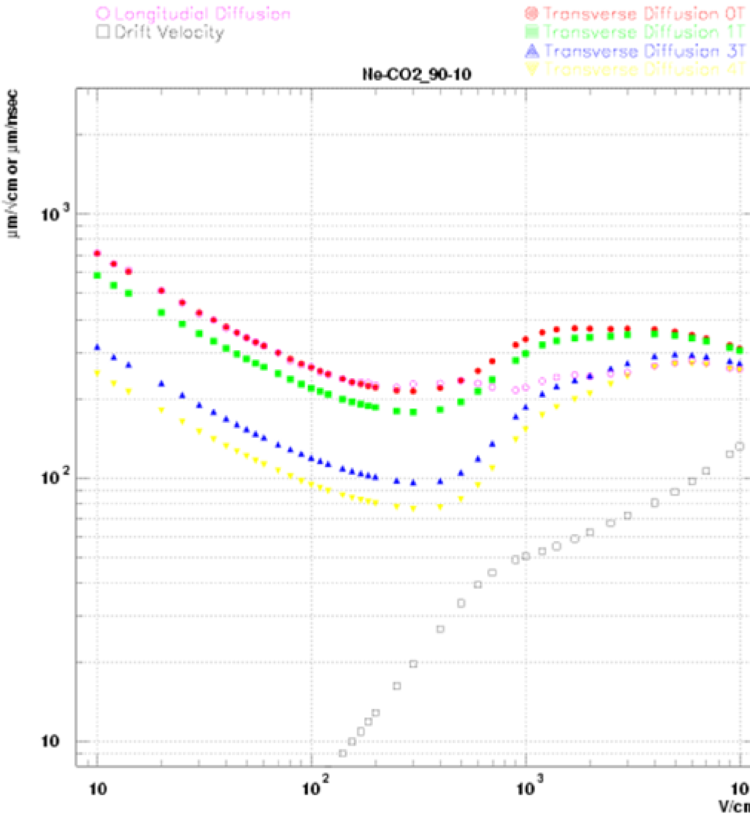
Dual-GEM + μMEGA Solution from Yale





Gas Considerations





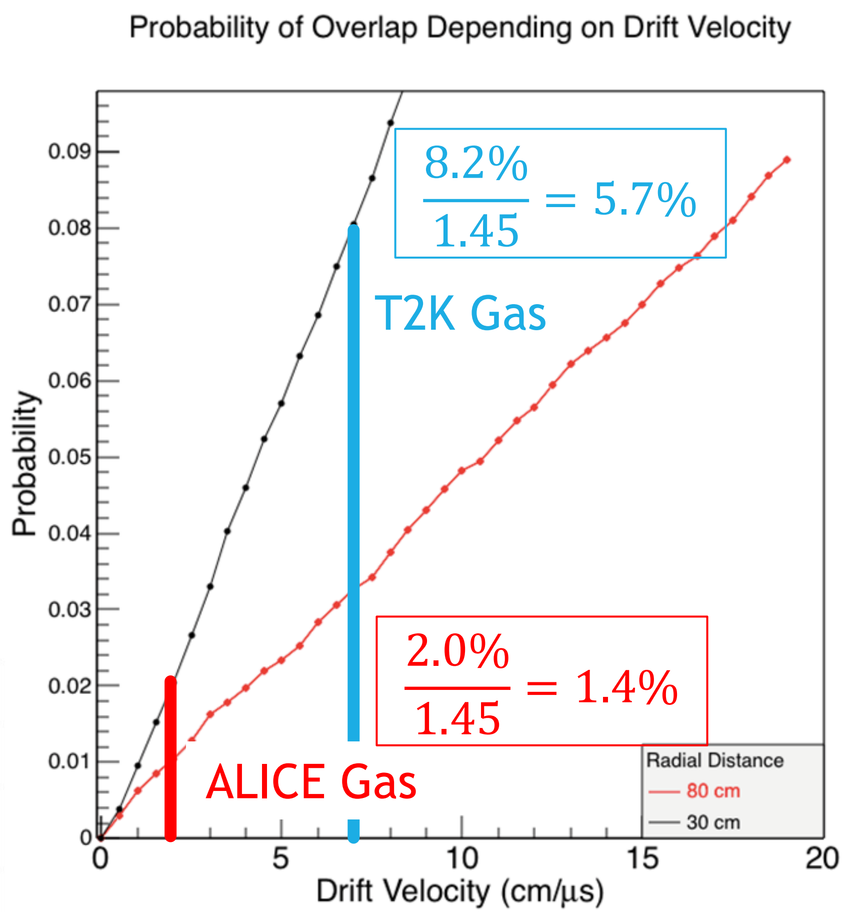
- Drift Velocity
  - Faster limits number of “stacked” evts
  - Slower improves two-particle resolution (Shaper-response-time driven).
- Longitudinal Diffusion
  - Less is better z (p_z) resolution.
  - Typically not momentum resolution limitation.
- Transverse Diffusion
  - Too large smears tracks together.
  - Too small amount fails to spread charge over electrodes. (sensitive to GEM hole geometry).
- Positive Ion Mobility
  - There is no up side to having positive ions in the gas volume.
  - Therefore higher mobility is always better.

Drift Velocity

- Faster drift means that the detector volume clears out faster.
- Fewer stacked events with v_d large.
- However, electronics response must be factored in:
  - SAMPA has 190 nsec peaking time (matched to ALICE).
  - Better matched to slow gas for high multiplicity applications.
  - Makes sense…ALICE uses slow gas.
- Even with ALICE slow gas sPHENIX will experience only between 1-2 stacked events on average.
- This is because the TPC is so much smaller than ALICE (Typically 5 evts stacked at full luminosity planned for future)

NOTE: A plateau in drift velocity is nice, but ALICE works on the rising edge!

SPECIFICATION	VALUE
Polarity	Pos/Neg
Detector capacitance	18pF - 25pF (TPC) 40pF – 80pF (MCH)
Peaking time	190ns - 300ns
Shaping	4th order
Sensitivity	12 - 9 - 6 – 3 mV/fC @1V ADC
Linear Range	1V @ 83fC, 110fC, 166fC, 330fC
Power consumption per channel (VDD=1.2V)	< 6mW (PASA: 11mW VDD = 3.3V)
Linearity	< 0.8%@ 12mV/fC

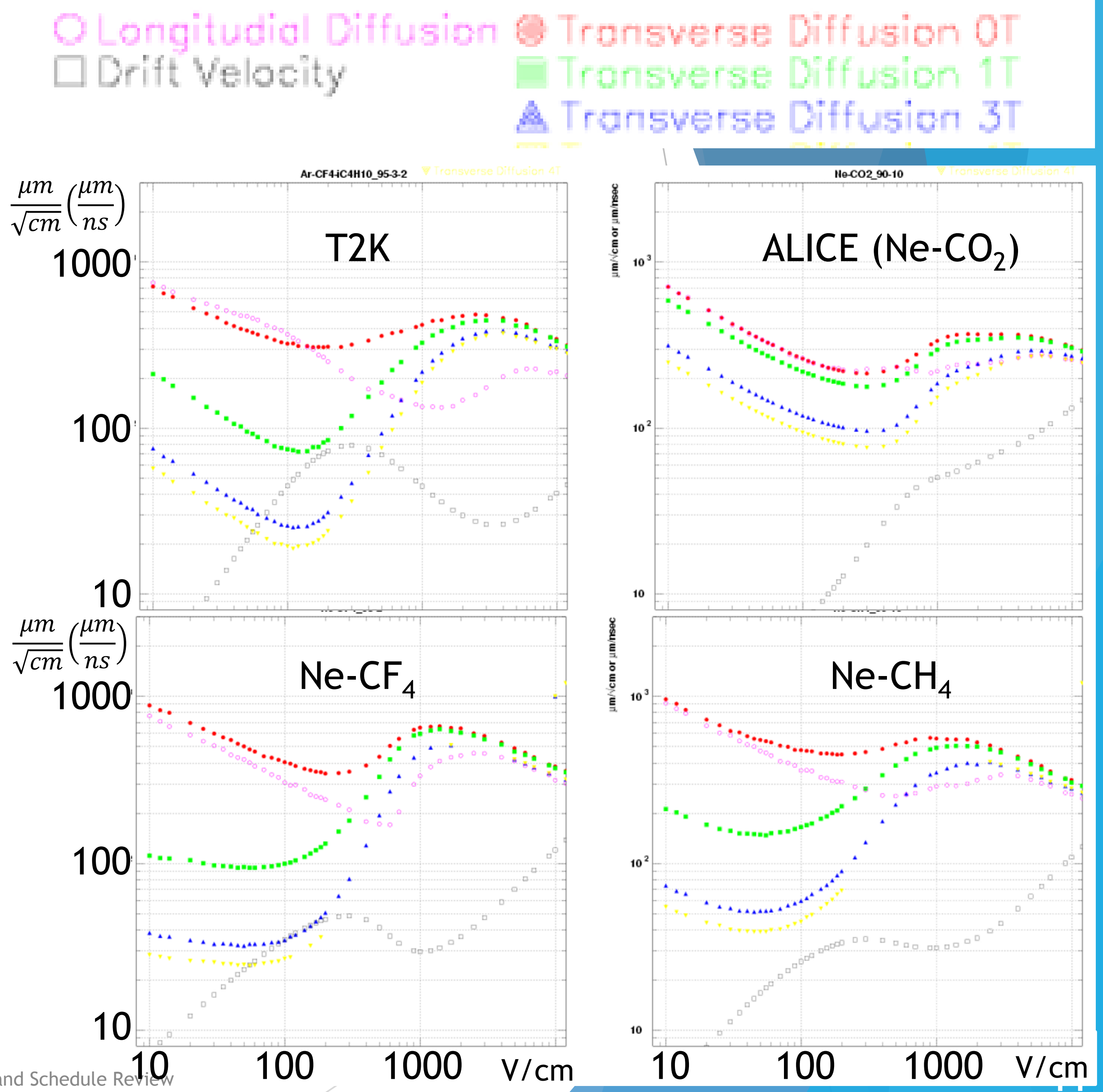


- "Voxel" occupancy assuming:
  - 1 degree in phi.
  - 200 nsec window in zed
- pCRD
  - 1.2mm pads; 3 pads per track;
  - 1.45X better than calculation.

Transverse Diffusion

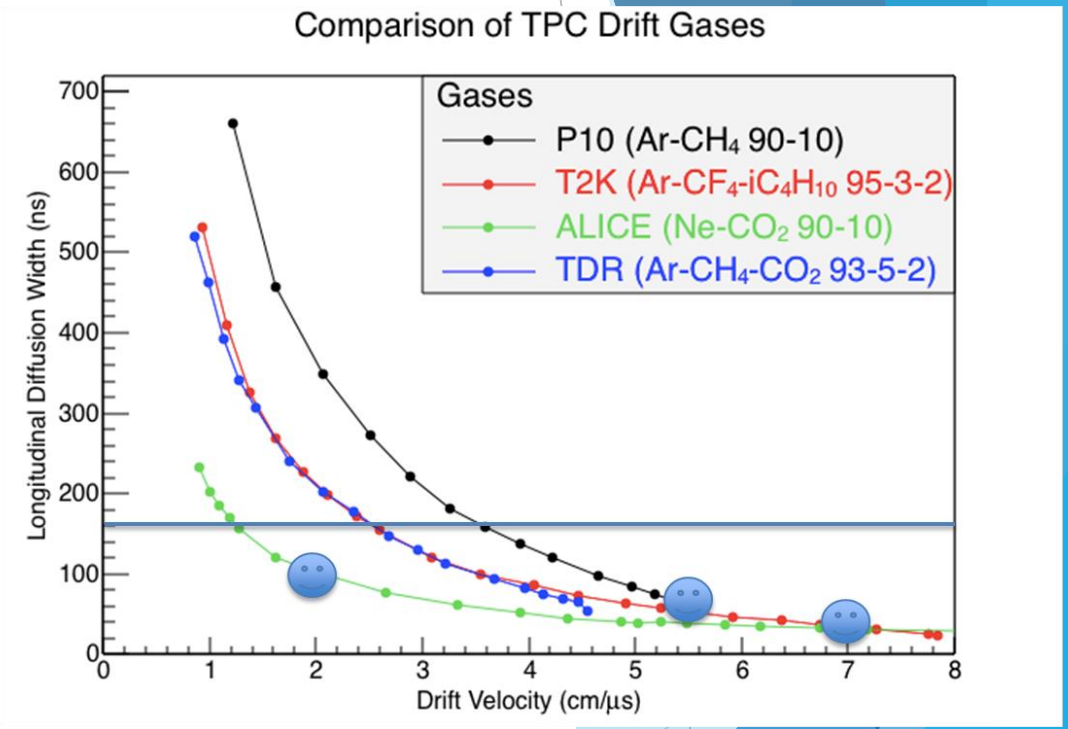
- Competing desires:
  - Position resolution. Containing charge well in the transverse direction improves position resolution partly through the use of smaller pads.
  - Finite count of pads. To get high resolution you must charge share. Although "patterning" the pads (see talk by Bob Azmoun) allows for charge sharing even with large pads, one must stay within the boundaries of "printable pads"
    - Minimum feature size ~100 microns.
    - Limiting feature for electrode points.
  - Diffusion includes not only the drift volume, but the avalanche process that via GEM-Hole-misalignment adds an extra term.
  - Best case:
    - Small volume diffusion.
    - Reasonable avalanche diffusion (~500 microns?)

Life is MUCH EASIER for us than ALICE due to smaller pads



Longitudinal Diffusion

- Typically longitudinal position resolution is not the limiting factor for tracker momentum resolution.
- Therefore a diffusion spec should be matched to the shaping time of the electronics to insure linear response of the system for good dE/dx resolution.
- The line is set to ~2/3 of the peaking time and the smiley face icons are set to the drift velocity that minimizes transverse diffusion.
- All these gas choices match well with the SAMPA chip simply because ALICE is designing for slow gas.



Ion Mobility

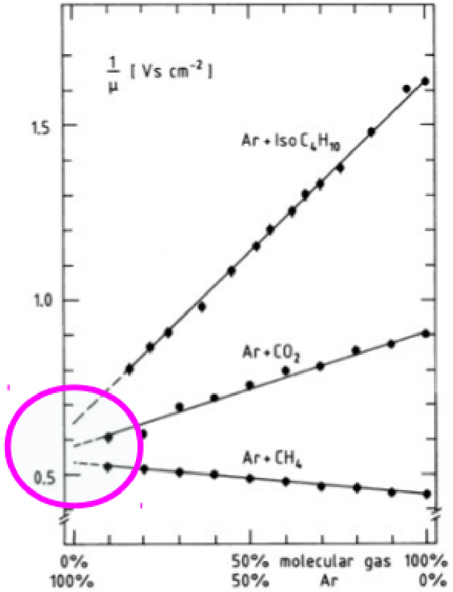
- This challenges one's belief in silver linings!
- I know of no good that comes from positive ions in the drift volume.
- The ion mobility itself is easy to calculate:
  - Independent of field for all reasonable E_{drift}

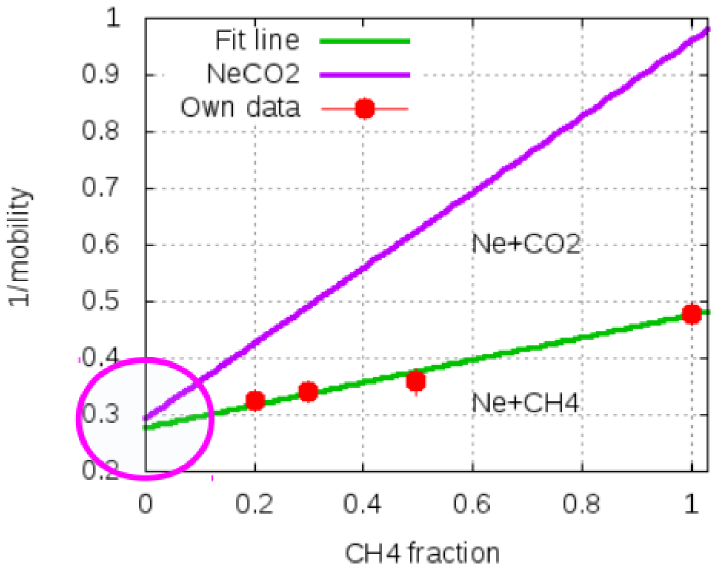
$$v_{ion\ drift} = KE$$

  - Easy to calculate for gas mixtures

$$\frac{1}{K_{TOT}} = f_1\frac{1}{K_{11}} + f_2\frac{1}{K_{22}}$$

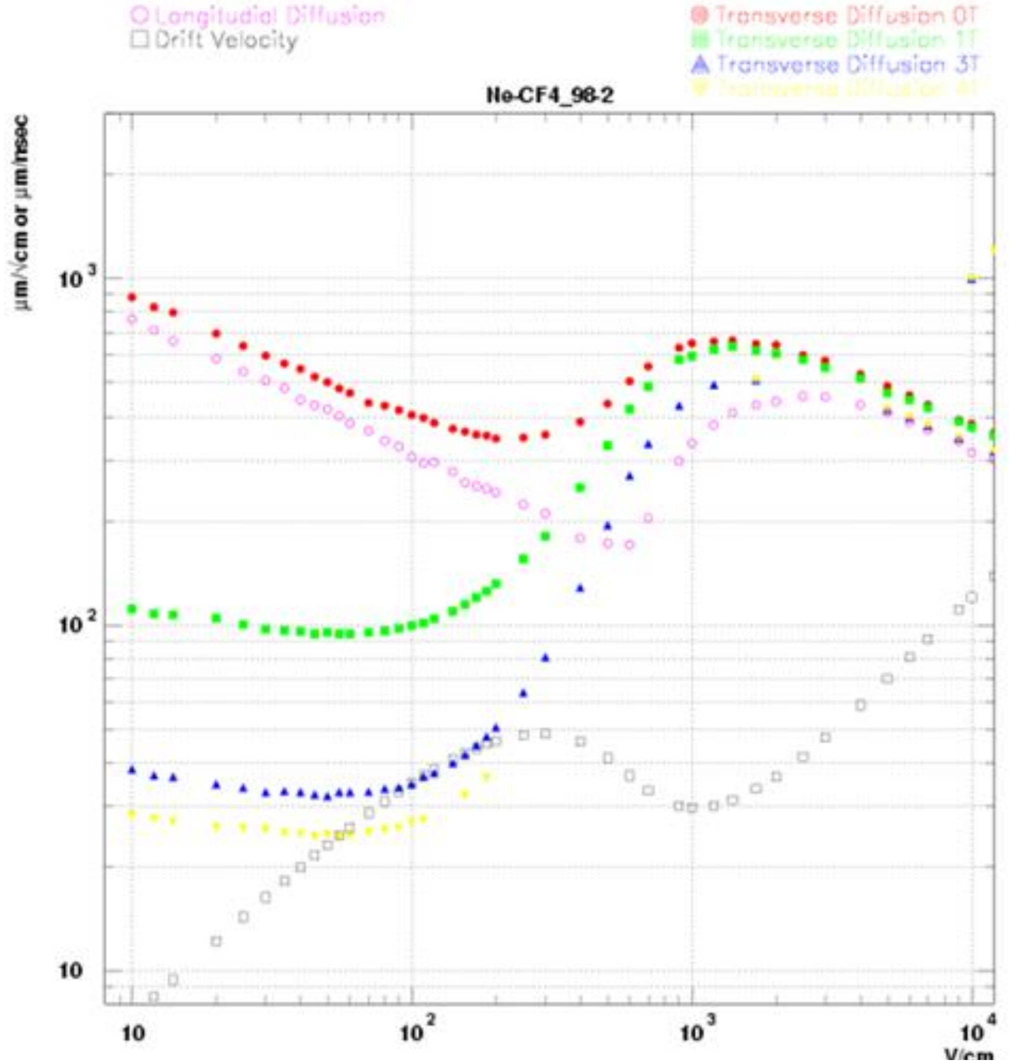
- ALICE Neon mixture helps (6X better than STAR)
- Reducing ion mobility requires low mass gasses neon-based mixture.
- We are now running the ALICE code to quantify these effects.

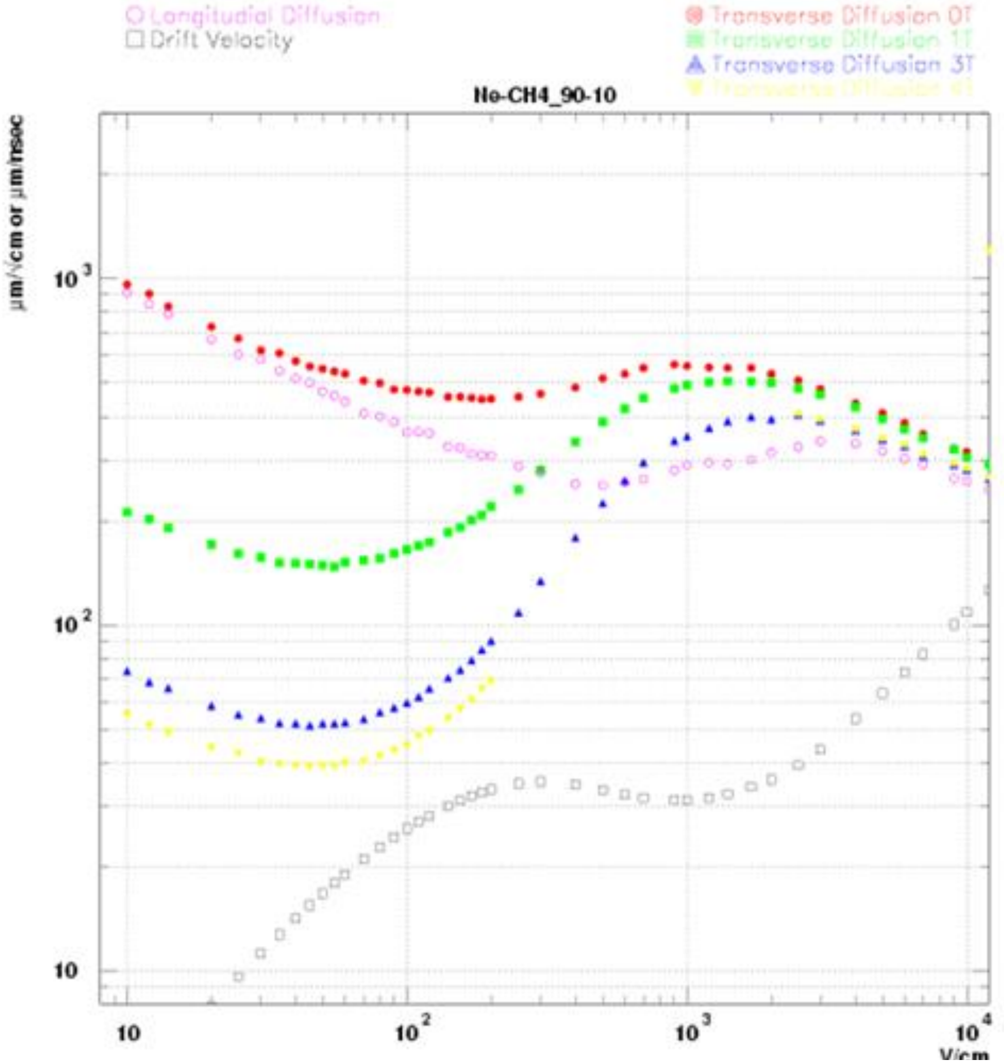




Gas	K ($\frac{cm^2}{Volt \cdot sec}$)	v_D ($E = 130\frac{V}{cm}$)	v_D ($E = 400\frac{V}{cm}$)
Ar	1.51	196	604
Ar-CH_4 90:10	1.56	203(STAR)	624
Ar-CO_2 90:10	1.45	189	582
Ne	4.2	546	1680
Ne-CH_4 90:10	3.87	503	1547
Ne-CO_2 90:10	3.27	425	1307(ALICE)
He	10.2	1326	4080
He-CH_4 90:10	7.55	981	3019
He-CO_2 90:10	5.56	722	2222
T2K	1.46	190(ILC)	584

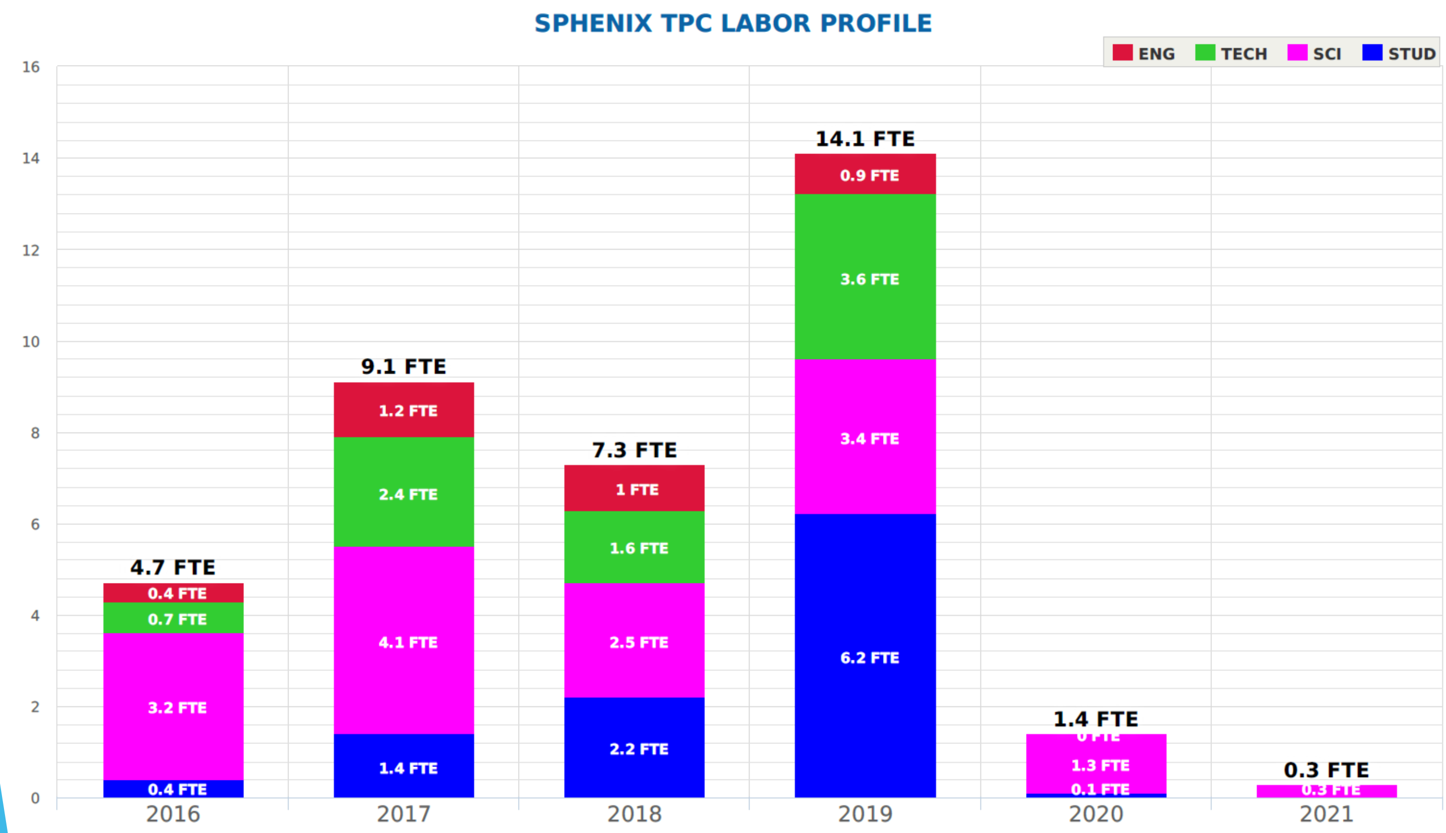
Possible gas choices?

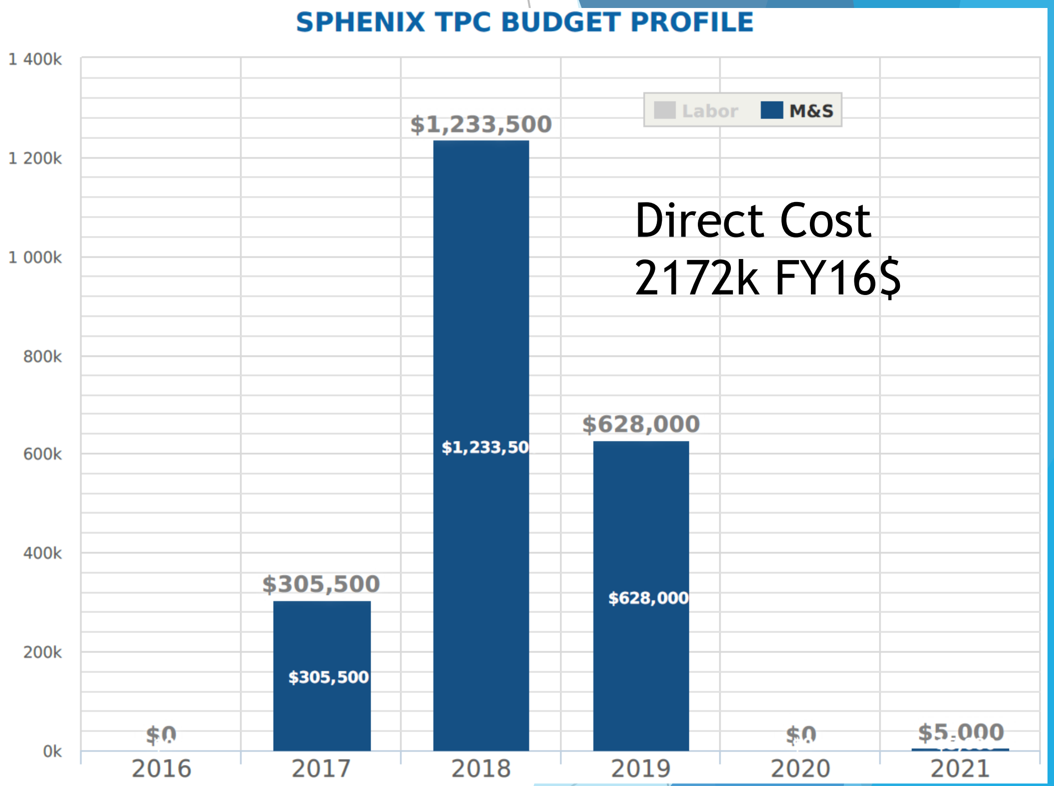




- ALICE provides “existence proof”.
- These options are at least as good, possible better. (Neon-based, good diffusion, good plateau)
- Presently formulating quantitative “Figure of Merit” to define a reference design.

Resource/Cost Drivers

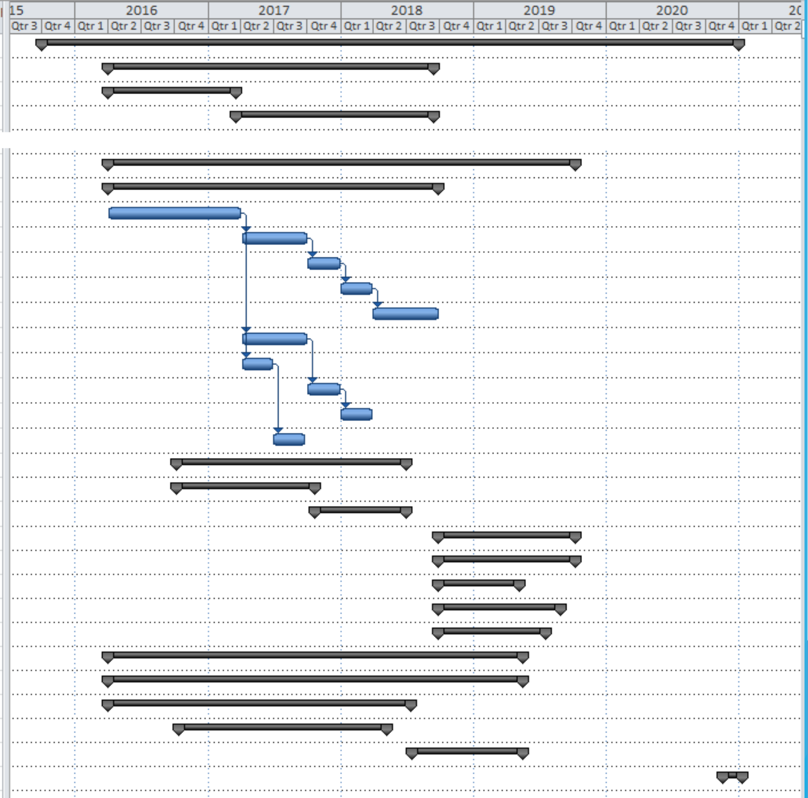




Direct Cost
2172k FY16$

Schedule Drivers

WBS	Task Name	Duration	Start	Finish
1.3.1	Tracker Management	1306 days	Thu 10/1/15	Wed 12/30/20
1.3.2	Pixel Detector	614 days	Fri 4/1/16	Fri 9/14/18
1.3.2.1	Pixel Design	239 days	Fri 4/1/16	Thu 3/16/17
1.3.2.2	Pixel Production	375 days	Fri 3/17/17	Fri 9/14/18
1.3.4	Time Projection Chamber	880 days	Fri 4/1/16	Wed 10/9/19
1.3.4.1	TPC Design	620 days	Fri 4/1/16	Mon 9/24/18
1.3.4.1.1	Specify Design	250 days	Fri 4/1/16	Fri 3/31/17
1.3.4.1.2	Design mechanical support structure	125 days	Mon 4/3/17	Thu 9/28/17
1.3.4.1.3	Design exterior gas enclosure	60 days	Fri 9/29/17	Thu 12/28/17
1.3.4.1.4	Design field cage	60 days	Fri 12/29/17	Tue 3/27/18
1.3.4.1.5	Design central membrane	125 days	Wed 3/28/18	Mon 9/24/18
1.3.4.1.6	Design end plate cage	125 days	Mon 4/3/17	Thu 9/28/17
1.3.4.1.7	Design gas system	60 days	Mon 4/3/17	Mon 6/26/17
1.3.4.1.8	Design pad plane	60 days	Fri 9/29/17	Thu 12/28/17
1.3.4.1.9	Design GEMs and framing	60 days	Fri 12/29/17	Tue 3/27/18
1.3.4.1.10	Design cooling	60 days	Tue 6/27/17	Thu 9/21/17
1.3.4.2	TPC Prototype	432 days	Wed 10/5/16	Fri 6/29/18
1.3.4.2.1	TPC Prototype v2	261 days	Wed 10/5/16	Fri 10/20/17
1.3.4.2.2	TPC Preproduction Prototype	171 days	Mon 10/23/17	Fri 6/29/18
1.3.4.3	TPC Production	260 days	Mon 9/24/18	Wed 10/9/19
1.3.4.3.1	TPC Module Production	260 days	Mon 9/24/18	Wed 10/9/19
1.3.4.3.2	TPC Laser System	154 days	Tue 9/25/18	Wed 5/8/19
1.3.4.3.3	TPC Gas System	230 days	Tue 9/25/18	Tue 8/27/19
1.3.4.3.4	TPC Cooling System	202 days	Tue 9/25/18	Thu 7/18/19
1.3.4.4	TPC Electronics	780 days	Fri 4/1/16	Thu 5/16/19
1.3.4.4.1	TPC Frontend Electronics Card	780 days	Fri 4/1/16	Thu 5/16/19
1.3.4.4.1.1	TPC FEC Design	570 days	Fri 4/1/16	Fri 7/13/18
1.3.4.4.1.2	TPC FEC Prototype	390 days	Thu 10/13/16	Tue 5/8/18
1.3.4.4.1.3	TPC FEC Production	210 days	Mon 7/16/18	Thu 5/16/19
1.3.5	Final Tracker Assembly/Testing Integration	35 days	Mon 11/16/20	Mon 1/11/21

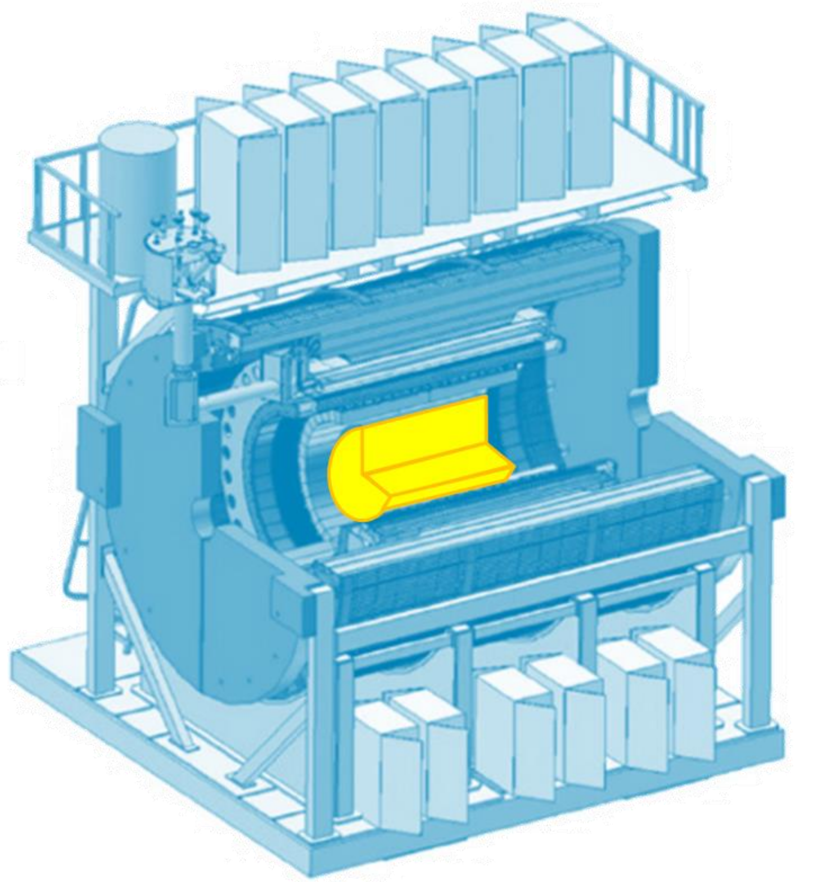


NOTE: Assumes project funds ~July 2018, consistent w/ guidance from Project Management.

- Prototyping Stages (front loaded)
  - v1: Final field cage; instrument single module of some technology (TBD); "shelf" electronics; no cooling.
  - v2: Improved module design; connector pattern final; shelf electronics; no cooling.
  - Pre-prod: Final module design; SAMPA.
- The critical path for the TPC system runs through the prototyping stage.
- Detector "Production" requires construction of final set of modules following pre-production design.

Summary

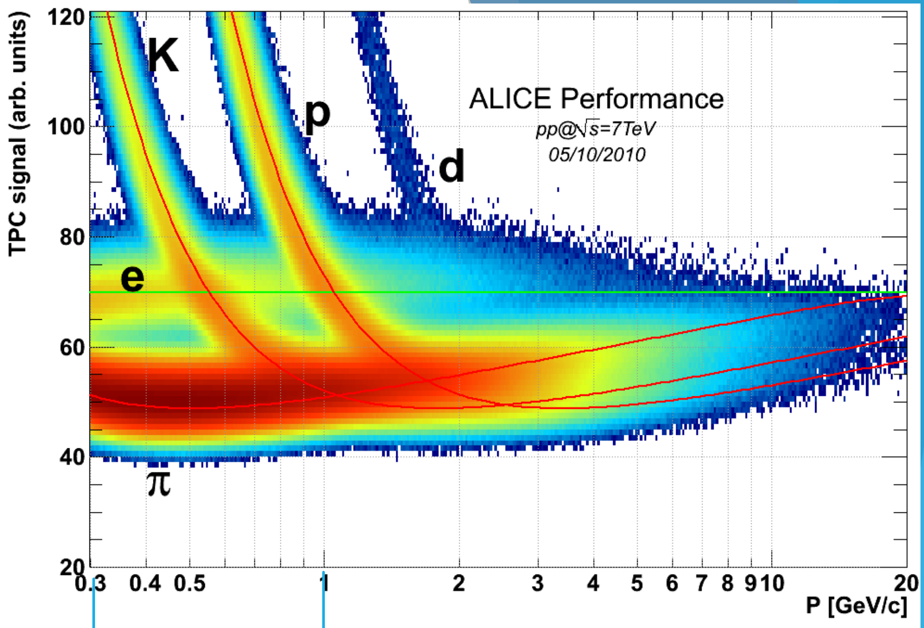
- Consistent with the charge of maintaining long term viability of the tracking technology we are purposely developing competing alternatives:
  - Inner Vertex Detector
    - Reuse PHENIX pixels
    - MAPS technology
  - Outer Tracker
    - Silicon Strip Detector
    - TPC
- All of these technologies have been shown to meet the physics requirements for heavy ion collisions with varying performance, risk, and utility for longer term use.
- The TPC option requires detailed consideration of design choices to deduce the best balance of operating parameters.
- ALICE is likely to succeed and would thereby represent an initial straw design, but we can also fine tune to our needs.
- dE/dx capability provides long term viability into EIC era.

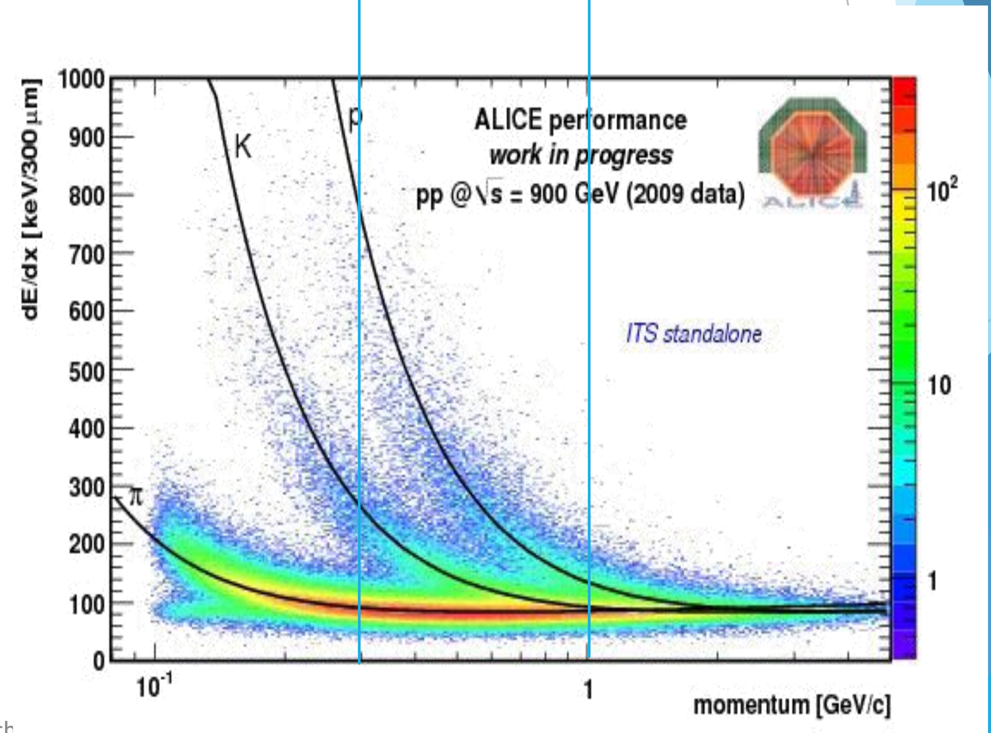


BACKUPS

Solid vs Gas dE/dx

- Gas detectors provide PID via dE/dx out to significantly higher momentum due to differences in the behavior of the talk in the relativistic rise region.
- STAR uses this to identify low momentum electrons for their dielectron and J/Psi results.
- Not simulated yet, but this could restore some dielectron capability for masses below the upsilon.





Issues and Concerns

	Issue/Concern
Technology Downselect	Timeline and Criteria
Reused pixels	Gaps (non-overlaps) and dead pixels.
Strips	Small margin on S1 thickness constraint before out of spec; alleviated by increased radius and cost.
SAMPA Chip	Timeline for chip production; integration w/ DAQ
Ion Back Flow	Resolution with space charge distortions.
High Voltage	Single point of failure using solid for HV.
TPC Field Map	What is and do we achieve the desired uniformity/measurement
Data Volume for continuous readout.	
Connection of TPC→Silicon	

Design Drivers-II

- The list of considerations necessary to realize the hybrid option is significant.
- More detail will be available in the afternoon session.
- Here we summarize some of the challenges facing our design.

	Comment 1	Comment 2
Chevron Pads	Good charge sharing for low diffusion gasses	Asserts a (correctable) diff. non-linearity
GEM gain stages	High rate capable (vs wire chamber)	Gain uniformity and drift; longevity
SAMPA Chip	TPC-specific chip, Continuous readout	Does not exist, long peaking time-190ns
Ion Back Flow	Tunable IBF vs dE/dx resolution	No TPC yet operated this way.
High Voltage	Known solids capable w/ safety margin.	Solids introduce single point failure.
Diffusion	Small diff improves resol, collection time	Diff assists spreading charge over pads.
Electron v_D	Fast lowers stacked evts; plateau desirable.	Slow lowers “voxel occupancy”
Noble Gas	Ar mix: nice plateau; low field; low ion mobility (therefore lots of space charge)	Ne mix: much higher ion mobility, no plateau, high V_{CM}
dE/dx		

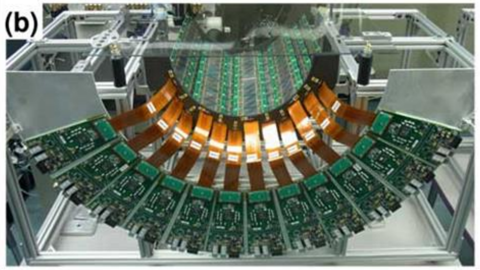
More work required to prove viability of hybrid design.

Description of Subsystem Options

- Inner Vertex Detector ($\sigma_{DCA} < 100\ \mu m$)
  - Reuse existing PHENIX VTX pixel detector.
  - MAPS Technology ($e.g.$ ALICE ITR Upgrade)
- Outer Tracker ($\sigma_m < 100\ \frac{MeV}{c^2}\ @\ 9\frac{GeV}{c^2}$)
  - Silicon Strip Detector
  - Non-gated TPC (Hybrid means TPC+reuse)

Reuse PHENIX VTX Components

- Momentum Resolution Limited by Multiple Scattering.
- Significant Dead Area (non-working & gaps)

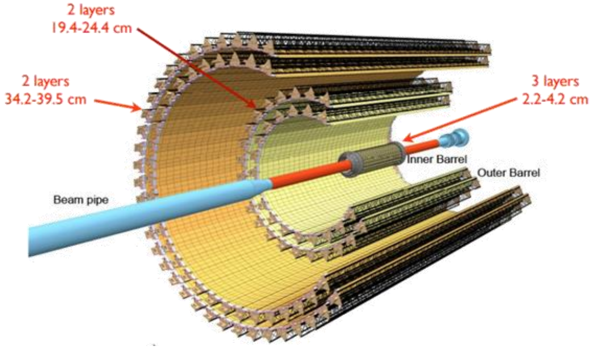


ALICE ITS upgrade detector

All layers composed of pixels.
- Inner three layers: 0.3% / layer
- Outer four layers: 0.8% / layer

Total thickness X/X_0 = 4.1%

Pixel sizes:
inner barrel 20-30 x 20-30 μm
outer barrel 20-50 x 20-50 μm



Reference

NOTE: Existing PHENIX pixel detector currently achieves 100 μm DCA resolution. MAPS technology would only improve this due to smaller pixels and less material.

New PHENIX-like Components

- Straightforward technology.
- Fast (no event pileup).
- Multiple-Scat limited.
- Little PID capability

Compact TPC (ala ALICE?)

- Higher momentum resolution
- Smaller Bremsstrahlung tails.
- Leverage ALICE R&D
- PID via dE/dx & neutral V's.

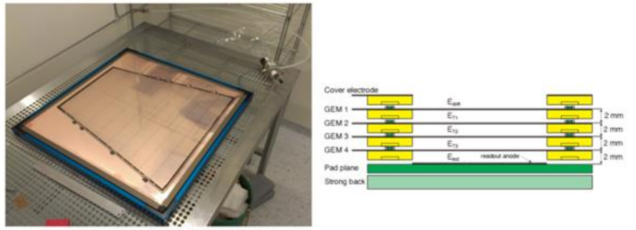


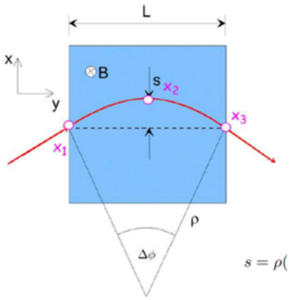
Figure 4.7: Photograph of an IROC GEM foil in the stretching frame.

Reference

Comparison requires detailed simulation.

Momentum Resolution-I

Position Resolution:
(Silicon best)

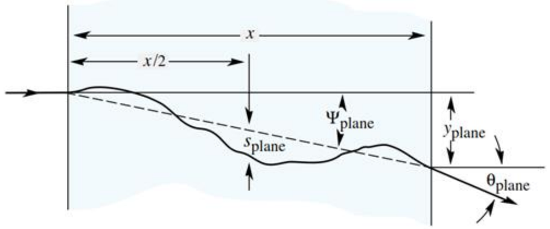


$$s = \rho\left(1-\cos\frac{\Delta\phi}{2}\right) \approx \rho\left(1-\left(1-\frac{1}{2}\frac{\Delta\phi^2}{4}\right)\right) = \rho\frac{\Delta\phi^2}{2} \approx \frac{0.3}{8}\frac{L^2B}{p_T}$$

$$\frac{\sigma_{p_T}}{p_T} = \frac{\sigma_s}{s} = \frac{8\sigma_s}{0.3L^2B}p_T$$

$$\boxed{\frac{\sigma_{p_T}}{p_T} = \sqrt{\frac{720}{(N+4)}}\frac{\sigma_x}{0.3L^2B}p_T}$$

Multiple Scattering:
(Hybrid better)



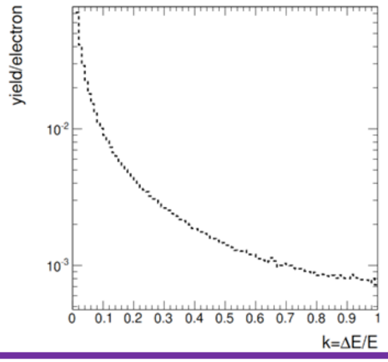
$$\phi_0 = \frac{13.6\mathrm{MeV}}{\beta c p_T} z\sqrt{\frac{L}{X_0}}\left[1+0.038\ln\frac{L}{X_0}\right]$$

$$\boxed{\frac{\sigma_{p_T}^{ms}}{p_T} = \frac{0.052}{\beta BL}\sqrt{\frac{L}{X_0}}\left[1+0.038\ln\frac{L}{X_0})\right].}$$

3 Dimensions:

$$\boxed{\frac{\sigma_p}{p} = \sqrt{\left(\frac{\sigma_{ms}}{\sqrt{\sin\theta}}\right)^2 + \left(\sigma_{det}\ p\sin\theta\right)^2 + \left(\sigma_\theta^{det}\ \cot\theta\sin\theta\right)^2 + \left(\frac{\sigma_\theta^{ms}}{\sqrt{\sin_\theta}}\frac{\cot\theta}{p}\right)^2}}$$

Bremsstrahlung:
(Hybrid better)



$$k \equiv \frac{\Delta E}{E} \qquad \frac{d\sigma}{dk} = \frac{A}{X_0 N_A k}\left(\frac{4}{3}-\frac{4}{3}k+k^2\right)$$

$$\boxed{N_\gamma = \frac{L}{X_0}\left(\frac{4}{3}\ln\frac{k_{max}}{k_{min}} - \frac{4(k_{max}-k_{min})}{3} + \frac{k_{max}^2-k_{min}^2}{2}\right)}$$

Tracking Systems (Practice)

Momentum Resolution calculated for all options from analytic and full Monte Carlo Simulations

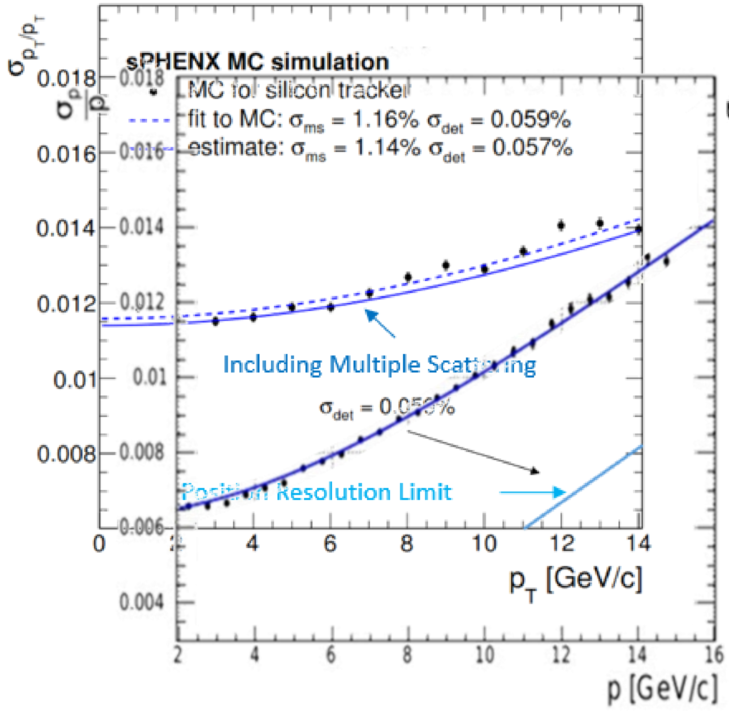
Momentum Resolution-II

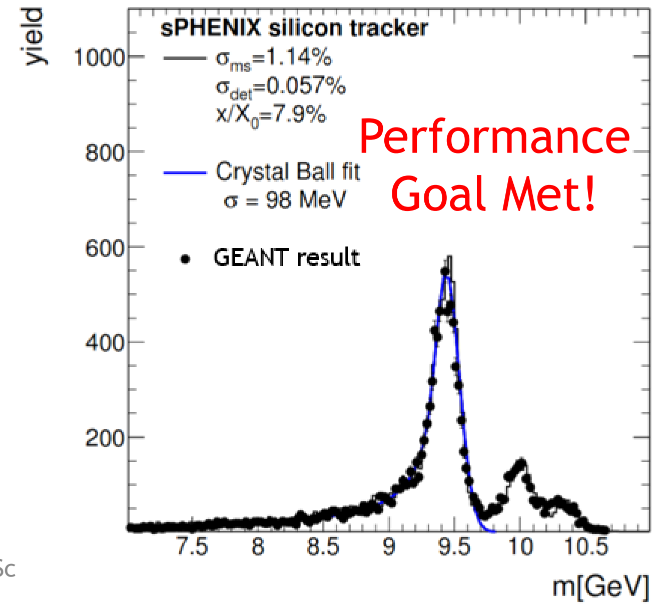
Station	Layer	radius (cm)	pitch (μm)	sensor length (cm)	depth (μm)	total thickness X_0%	area (m^2)
Pixel	1	2.4	50	0.425	200	1.3	0.034
Pixel	2	4.4	50	0.425	200	1.3	0.059
S0a	3	7.5	58	9.6	240	1.0	0.10
S0b	4	8.5	58	9.6	240	1.0	0.12
S1a	5	31.0	44	9.6	240	0.6	1.6
S1b	6	34.0	44	9.6	240	0.6	2.0
S2	7	64.0	60	9.6	320	1.0	6.9

layer	radius (cm)	total thickness % X_0	$\Delta L/L$	c_{ms} (mrad)	σ_{ms} (mrad)
VTX 1	2.7	1.3	0.95	1.8	1.7
VTX 2	4.6	1.3	0.92	1.8	1.7
air	15	0.1	0.73	0.03	0.02
field cage	30	1.0	0.45	1.12	0.5

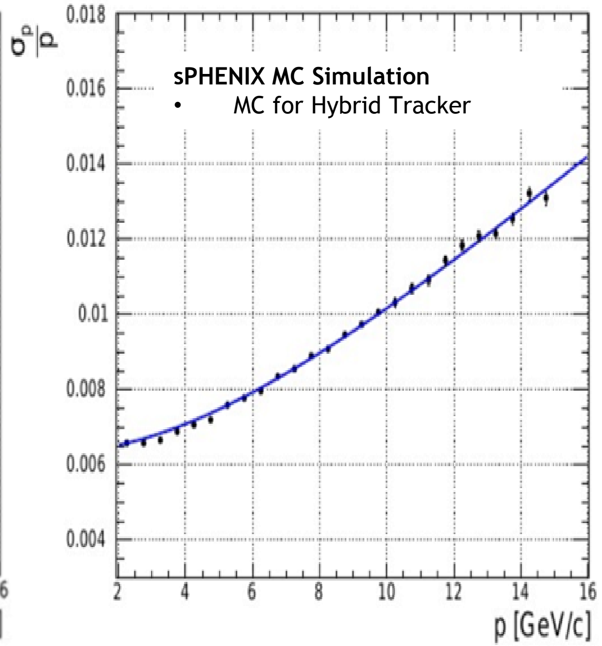
- Analytic and full Geant simulations performed.
- All results agree remarkably well.
- All options meet the experiment design goal.

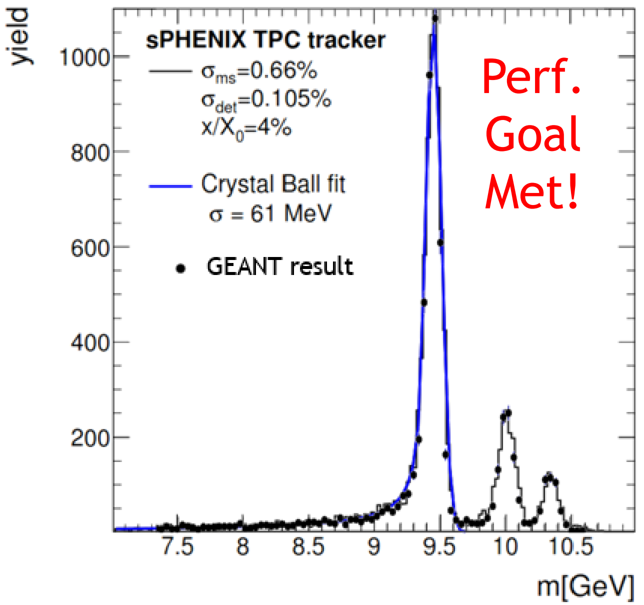
Baseline Design





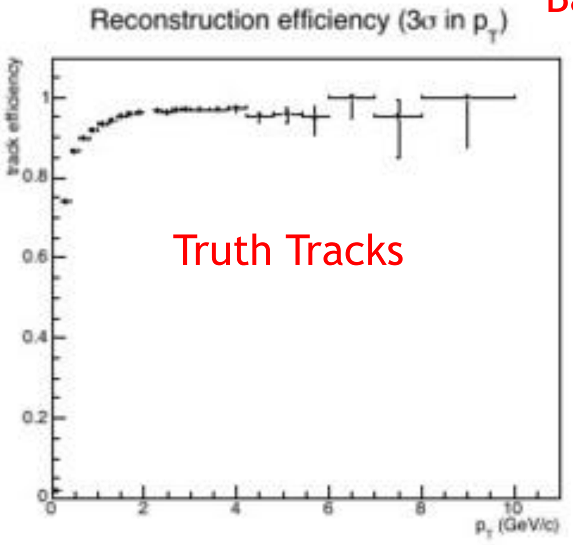
Hybrid: Reuse Pixels + TPC

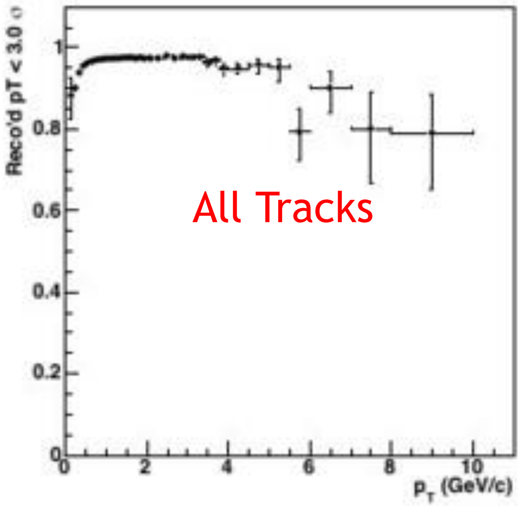




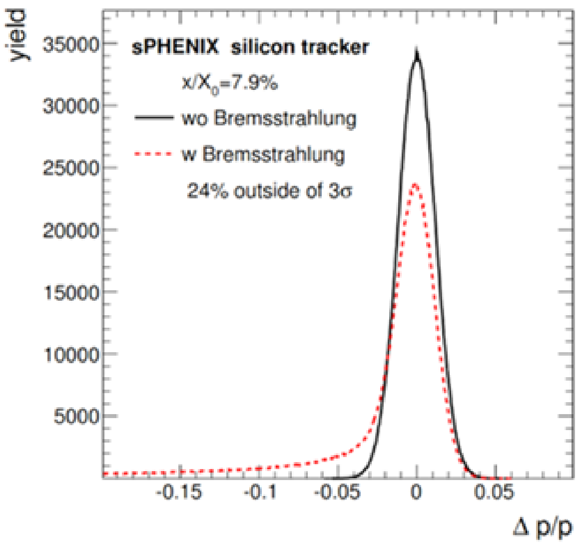
Reconstruction Efficiency

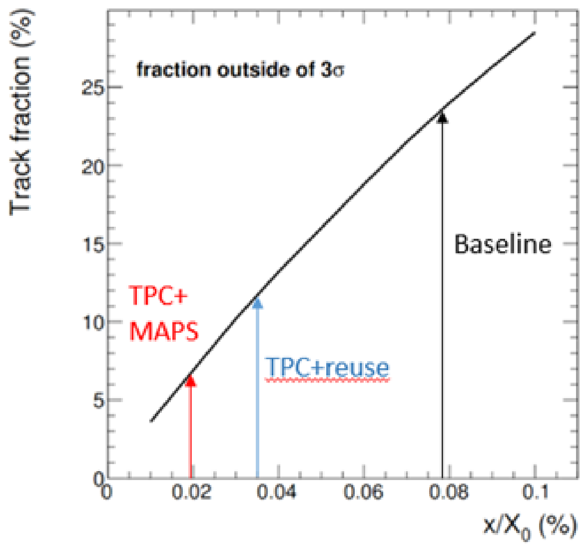
Baseline: Pions in Central HIJING





Bremsstrahlung-induced Efficiency Losses





- Monte Carlo reconstruction of pion tracks demonstrates that the baseline detector version performs remarkably well for pions in HIJING.
- Electron tracks will also suffer Bremsstrahlung losses forcing them outside the 3σ window.
- These losses are tolerable even in the thickest design option.

	Electron Singles (loss/efficiency)	Electron Pairs (loss/efficiency)
Baseline	24% / 76%	42% / 58%
Reuse + TPC	12% / 88%	23% / 77%
MAPS + TPC	7% / 93%	12% / 88%

Design Drivers

Baseline Option

Station	Layer	radius (cm)	sensor pitch (μm)	sensor length (cm)	sensor depth (μm)	total thickness X_0%	area (m^2)
Pixel	1	2.4	50	0.425	200	1.3	0.034
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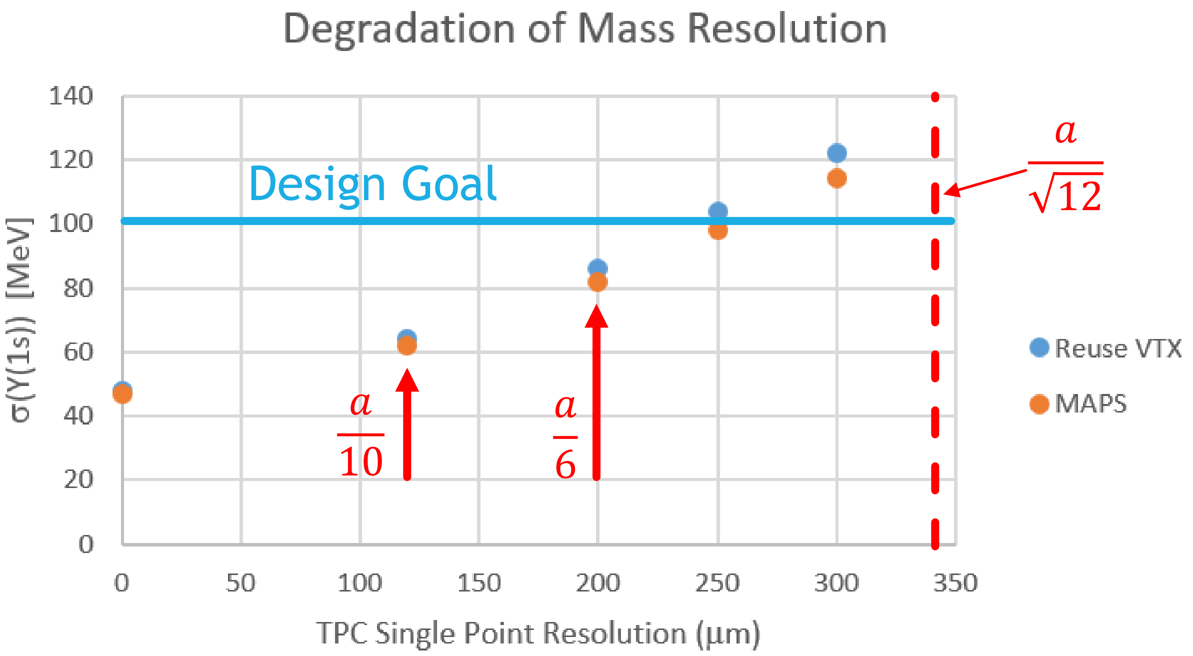
S2	7	64.0	60	9.6	320	1.0	6.9

- In many ways, a multiple-scattering limited spectrometer is robust against:
  - Single point resolution.
  - Alignment.
  - Detector "creep"
- The design must maintain thin detectors in the middle layers (dominant contributors to the sagitta determination).
- Mass resolution (currently ~10% better than required) will degrade linearly with the thickness of the S1 layer.
- We can therefore tolerate a roughly 10% increase in the S1 thickness above the current design spec. w/o changing the design toward larger r

Hybrid Tracker Option



- The Upsilon mass width for the hybrid setup is dominated by the single point resolution.
- Current calculations assume an RMS resolution of 1/10 the pad size ($\frac{a}{10}$).
- The hybrid system will meet the design goal with an RMS resolution as bad as 250 μm.